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CN and HNC line emission in IR luminous galaxies

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Abstract. We have observed HNC 1–0, CN 1–0 & 2–1 line emission in a sample of 13 IR luminous (LIRGs, $L_{\rm IR} > 10^{11}$ $L_\odot$) starburst and Seyfert galaxies. HNC 1–0 is detected in 9, CN 1–0 is detected in 10 and CN 2–1 in 7 of the galaxies and all are new detections. We also report the first detection of HC_3N (10–9) emission in Arp 220. The excitation of HNC and CN emission requires densities $n > 10^4$ cm^{-3}. We compare their intensities to that of the usual high density tracer HCN. *The* $\frac{I({\rm HCN})}{I({\rm HNC})}$ *1–0 and* $\frac{I({\rm HCN})}{I({\rm CN})}$ *1–0 line intensity ratios vary significantly, from 0.5 to* $\gtrsim$*6, among the galaxies.* This implies that the actual properties of the dense gas is varying among galaxies who otherwise have similar $\frac{I({\rm CO})}{I({\rm HCN})}$ line intensity ratios. We suggest that the HNC emission is not a reliable tracer of cold (10 K) gas at the center of LIR galaxies, as it often is in the disk of the Milky Way. Instead, the HNC abundance may remain substantial, despite high gas temperatures, because the emission is emerging from regions where the HCN and HNC formation and destruction processes are dominated by ion-neutral reactions which are not strongly dependent on kinetic temperature. We find five galaxies (Mrk 231, NGC 7469, NGC 7130, IC 694 and NGC 2623) where the $\frac{I({\rm HCN})}{I({\rm HNC})}$ intensity ratio is close to unity. Four are classified as active galaxies and one as a starburst. In other active galaxies, however, the $\frac{I({\rm HCN})}{I({\rm HNC})}$ is >4. The CN emission is on average a factor of two fainter than the HCN for the luminous IR galaxies, but the variation is large and there seems to be a trend of reduced relative CN luminosity with increasing IR luminosity. This trend is discussed in terms of other PDR tracers such as the [C II] 158 μm line emission. One object, NGC 3690, has a CN luminosity twice that of HCN and its ISM is thus strongly affected by UV radiation. We discuss the $\frac{I({\rm HCN})}{I({\rm HNC})}$ and $\frac{I({\rm HCN})}{I({\rm CN})}$ line ratios as indicators of starburst evolution. However, faint HNC emission is expected both in a shock dominated ISM as well as for a cloud ensemble dominated by dense warm gas in the very early stages of a starburst. Additional information will help resolve the dichotomy.

Key words. galaxies: evolution – galaxies: ISM – galaxies: starburst – radio lines: galaxies – radio lines: ISM

1. Introduction

The polar molecule HCN (dipole moment 2.98 debye) is commonly used as a tracer of dense molecular gas, i.e. gas at $n({\rm H_2}) \geq 10^4\,{\rm cm^{-3}}$. In particular in distant luminous ($L_{\rm IR} > 10^{11}$ $L_\odot$, LIRGs) and ultraluminous ($L_{\rm IR} > 10^{12}$ $L_\odot$, ULIRGs) systems the HCN 1–0 line is the prototypical tracer of dense gas content (e.g., Solomon et al. 1992; Helfer & Blitz 1993; Curran et al. 2000 (CAB)). Solomon et al. (1992) find a tighter correlation between FIR and HCN luminosity than the one found between FIR and CO. They suggest that, in general, the IR luminosities originate from star formation rather than AGN activity in FIR luminous galaxies. The HCN to CO intensity ratio, however, varies substantially ($\frac{1}{3}$–$\frac{1}{40}$) among luminous galaxies, and it is unclear whether this difference can simply be interpreted as variations in the dense gas content or is also due to abundance and/or excitation effects. Apart from being collisionally excited, HCN may become excited via electron collisions (at $X(e) \approx 10^{-5}$) or be pumped by 14 μm continuum radiation through vibrational transitions in its degenerate bending mode. It is also difficult to know if the gas is really engaged in star formation, or if it is simply dense in response to being near the central potential of the galaxy (e.g., Helfer & Blitz 1993; Aalto et al. 1995) where other mechanisms (AGN, turbulence etc.) may heat the gas and dust.

In order to understand the activities in the centers of luminous galaxies it is essential to also understand the prevailing conditions of the dense gas. Apart from observing higher transitions of HCN it is important also to study the emission from other high density tracers.

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One such tracer is the HNC molecule, the isomer of (and chemically linked to) HCN. For example, at high temperatures HNC can be transferred into HCN via the reaction HNC + H $\rightarrow$ HCN + H. It is predicted, e.g. in (maybe oversimplified) chemical steady state models, but also by shock models, that the $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ ratio increases with increasing temperature and gas density (e.g., Schilke et al. 1992 (S92)). This is supported by the fact that the measured $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ abundance ratio is especially high in the vicinity of the hot core of Orion KL. Most of the temperature dependence is between 10 and 50 K, after which there is a considerable flattening (S92).

Compared to these results, the $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ intensity ratios found (so far) in nearby starburst galaxies are rather low (ranging from 1–5) closer to dark clouds than to hot cores (Hüttemeister et al. 1995 (H95)). This result is in apparent contradiction with the idea that the gas is warm ($T \gtrsim 50$ K) in the centers of starburst galaxies (e.g., Wild et al. 1992; Wall et al. 1993). However, Aalto et al. (1995) suggest that the dense cores of the molecular clouds of the starburst NGC 1808 are cold (10 K) and thus these cores could be responsible for the HNC emission in NGC 1808, but possibly also in other galaxies.

The radical CN is another tracer of dense gas, with a somewhat lower (by a factor of 5) critical density than HCN. Observations of the CN emission towards the Orion A molecular complex (Rodriguez-Franco et al. 1998) show that the morphology of the CN emission is dominated by the ionization fronts of the HII regions. The authors conclude that this molecule is an excellent tracer of regions affected by UV radiation. Thus, the emission from the CN molecule should serve as a measure of the relative importance of gas in Photon Dominated Regions (PDRs).

We have searched for HNC and CN emission in a sample of LIRG and ULIRG galaxies with warm ($\frac{f(60\,\mu\mathrm{m})}{f(100\,\mu\mathrm{m})} \gtrsim 0.75$) FIR colours. We were interested to see whether the HNC emission would be relatively fainter compared to the cooler, nearby objects studied by H95. Is HNC a reliable cold gas tracer, or would we find evidence for the contrary? We furthermore wanted to assess the relative importance of dense PDRs in these objects through comparing the CN line brightness with that of HCN. If indeed the HNC emission is a tracer of the amount of cold, dense gas, then perhaps an anti-correlation between the CN and HNC emission is to be expected. Many of the galaxies in the survey are powered by prodigious rates of star formation and thus a bright CN line relative to HCN is to be expected. Some of the galaxies are dominated by an AGN where the CN brightness may also be high (e.g., Krolik & Kallman 1983).

In Sect. 2, we present the observations and in Sect. 3 the results in terms of line intensities and line ratios. In Sect. 4.1 we discuss the interpretation of the HNC results and in Sect. 4.2 we discuss CN. In Sect. 4.3 possible connections to starburst evolution and scenarios of the dominating gas components are discussed.

Table 1. Beamsizes and efficiencies.

Transition	ν [GHz]	HPBW [$''$]		η_{mb}	
		OSO	SEST	OSO	SEST
HCN 1–0	88.6	44	57	0.59	0.75
HNC 1–0	90.6	42	55	0.59	0.75
CN 1–0	113.5	34	46	0.50	0.70
CO 1–0	115.2	33	45	0.50	0.70

2. Observations

We have used the SEST and OSO 20 m telescope to measure the HNC 1–0 (90.663 GHz) and the CN 1–0 113.491 GHz (1–0, $J = 3/2$–$1/2$, $F = 5/2$–$3/2$) line intensity in a selection of 13 LIRGs and ULIRGs. We also include observations of NGC 1808 which is of lower luminosity. The selected galaxies all have global $\frac{I(\mathrm{CO})}{I(\mathrm{HCN})}$ 1–0 intensity ratios $\lesssim$15 (apart from NGC 3256 and NGC 1808). For the southern galaxies observed with SEST, we were also able to measure the CN 2–1 line (226.874 GHz (2–1, $J = 5/2$–$3/2$, $F = 7/2$–$5/2$), 226.659 GHz (2–1 $J = 3/2$–$1/2$ $F = 5/2$–$3/2$)). The CN 1–0 113.191 GHz line (1–0 $J = 1/2$–$1/2$ $F = 3/2$–$3/2$) is shifted +806 km s^{-1} from the main line and we have obtained limits to its intensity in several cases. For Arp 220 the two CN 1–0 spingroups are blended because the line is very wide. Thus, even in the 1 GHz correlator backend (see below) it was necessary to observe CN 1–0 at two different LO settings and then join the spectra together to get enough baseline. For four galaxies the bandwidth was wide enough to also include the 90.983 GHz 10–9 line of $\mathrm{HC_3N}$.

Observations were made in 1999 October (HNC, OSO), December (HNC, SEST) and 2000 June (CN, OSO), August (CN, SEST). For OSO, the system temperatures were typically 300 K for HNC and 500–600 K for CN. For SEST, typical system temperatures were 230 K for the HNC measurements and 400 K for both the 113 GHz and the 226 GHz CN observations. Pointing was checked regularly on SiO masers and the rms was found to be $2''$ for OSO, and $3''$ for SEST. Arp 220 was observed both with OSO (CN) and SEST (HNC). We have also measured the 115 GHz CO 1–0 and the HCN 1–0 lines for some galaxies where we did not have values from the literature. Beamsizes and efficiencies are shown in Table 1. For the OSO observations a 500 MHz filterbank was used for backends for all observations, and for some a 1 GHz autocorrelator was also used. For the SEST observations we alternated between a 500 MHz and 1 GHz backend depending on whether simultaneous observations with the 1 and 3 mm receiver were taking place. We used the software package xs (written by P. Bergman) to subtract baselines and add spectra.

Table 2. Integrated line intensities[a].

Galaxy	Telescope	v_c	I(HNC) 1–0[b]	I(CN) 1–0[c]	I(CN)2–1[d]	5/2–3/2	3/2–1/2	I(CO) 1–0
		$\mathrm{km\,s^{-1}}$	$\mathrm{K\ km\,s^{-1}}$	$\mathrm{K\ km\,s^{-1}}$	$\mathrm{K\ km\,s^{-1}}$	$\mathrm{K\ km\,s^{-1}}$	$\mathrm{K\ km\,s^{-1}}$	$\mathrm{K\ km\,s^{-1}}$
Arp 220	OSO	5400	...	2.0 ± 0.3	...	...	...	15.0 ± 2.0[g]
"	SEST	5400	0.95 ± 0.2	...	0.65 ± 0.2[h]	...	...	13.0 ± 2.0
IC 694[f]	OSO	3100	0.75 ± 0.2	$\lesssim$0.85	...	...	...	14.0 ± 1.0
NGC 3690[f]	OSO	3050	...	1.5 ± 0.3	...	...	...	11.0 ± 1.0
Mrk 231	OSO	12 650	0.5 ± 0.1	0.5 ± 0.2:	...	...	...	g
Mrk 273	OSO	11 320	$\lesssim$0.25	$\lesssim$0.25	...	...	...	g
NGC 34	SEST	5930	$\lesssim$0.3	$\lesssim$0.3	0.25 ± 0.05	...	...	5.5 ± 0.5[g]
NGC 1614	SEST	4500	...	0.6 ± 0.3:	0.5 ± 0.1	...	...	9.0 ± 0.5
NGC 2146	OSO	900	...	1.2 ± 0.3	...	...	...	43.0 ± 1.0
NGC 2623	OSO	5500	0.6 ± 0.15	$\lesssim$0.6	...	...	...	13.0 ± 0.5
NGC 6240	SEST	7335	0.4 ± 0.2:	0.7 ± 0.1	1.3 ± 0.1	0.9 ± 0.1[e]	0.4 ± 0.1[e]	15.5 ± 0.5
NGC 3256	SEST	2800	0.6 ± 0.05	1.2 ± 0.05	0.55 ± 0.05	0.4 ± 0.05	0.15 ± 0.05	45 ± 1.5
NGC 7130	SEST	4840	0.4 ± 0.05	0.5 ± 0.1	0.45 ± 0.05	0.3 ± 0.05	0.15 ± 0.05	9.5 ± 0.5[g]
NGC 7469	OSO	4960	0.7 ± 0.1	0.8 ± 0.1	...	...	...	g
NGC 1808	SEST	960	1.2 ± 0.1	3.8 ± 0.1	2.0 ± 0.1	1.4 ± 0.1	0.7 ± 0.1	66 ± 0.5

a) Integrated line intensities are in T_A^* and in $\mathrm{K\ km\,s^{-1}}$, and upper limits are all 3σ. SEST, $T_{\rm mb}$: 27 $\mathrm{Jy\,K^{-1}}$ (115 GHz), 41 $\mathrm{Jy\,K^{-1}}$ (230 GHz) for point sources; OSO, $T_{\rm mb}$: 27 $\mathrm{Jy\,K^{-1}}$ (115 GHz) for point sources.
b) In Arp 220 we also detect the 90.98 GHz (10–9) line of HC_3N with the intensity 0.4 ± 0.15. For NGC 3256 the (3σ) limit to the line is 0.18, for NGC 7130 it is 0.15, and for NGC 1808 we have a very tentative detection with the intensity 0.2 ± 0.1. For Arp 220 we also find an integrated HCN intensity in the SEST beam of 2.5 ± 0.4.
c) This is only the integrated intensity of the 1–0 $J = 3/2$–$1/2$ line. To get the total 1–0 intensity multiply with 1.3 (in the optically thin case). For Arp 220 both lines are blended and included in the integrated line intensity listed here.
d) The total integrated intensity from the two 5/2–3/2 and 3/2–1/2 spingroups together. The following two columns contain the integrated intensity in each spin group whenever it was possible to measure.
e) Line blending is severe therefore the intensity ratio was estimated from fitting of two Gaussians with fixed linewidths of $\Delta V = 450\ \mathrm{km\,s^{-1}}$ at $v_1 = 7200\ \mathrm{km\,s^{-1}}$ and $v_2 = 7500\ \mathrm{km\,s^{-1}}$.
f) IC 694 and NGC 3690 are also known as the merger Arp 299.
g) See CAB.
h) Very broad lines, may be affected by unknown baseline errors.

3. Results

3.1. HNC line intensities and ratios

The line intensities are presented in Table 2 and the ratios in Table 3. CO spectra are presented in Fig. 1 and HNC spectra (plus a SEST HCN spectrum for Arp 220) in Fig. 2. All galaxies, except NGC 1808, have FIR luminosities $L_{\rm FIR} \gtrsim 10^{11}\ L_\odot$ (see Table 3). Five of the investigated sources (Mrk 231, NGC 7469, NGC 2623, IC 694 and NGC 7130) have global $\frac{\rm HCN}{\rm HNC}$ luminosity ratios close to unity. The rest have ratios ranging from 2 to $\gtrsim$6. The HNC luminous objects are all AGNs (three Seyferts, one LINER (NGC 2623)) except for IC 694 which we suspect is a starburst (e.g., Polatidis & Aalto 2000), but there are also Seyfert galaxies with faint HNC emission (such as Mrk 273, NGC 6240 and NGC 34). We do not find that an increase in FIR luminosity is followed by an increase in $\frac{\rm HCN}{\rm HNC}$ line intensity ratio. Instead, there might be a weak trend to the opposite and two (Mrk 231 and Arp 220) of the three ULIRGs in our sample have relatively bright HNC emission (see Sect. 3.1.1).

3.1.1. Comparisons with other HNC surveys

In the H95 HNC survey of nearby starburst galaxies, the majority of the sources show $\frac{\rm HCN}{\rm HNC}$ line ratios greater than or equal to two. Three objects have I(HCN) $\approx$ I(HNC): the nearby starburst NGC 253, the nearby post-starburst NGC 7331 and the Seyfert NGC 3079. For most of the galaxies in that sample, the line ratios are not global, but reflect the conditions in the inner 0.2–1 kpc of the galaxy. Since both the HCN and CO emission for most of our sample galaxies comes from the inner kpc (e.g., Bryant 1996; Scoville et al. 1997; Downes & Solomon 1998; Bryant & Scoville 1999), it is meaningful to compare the $\frac{\rm HCN}{\rm HNC}$ ratios of the two samples. In H95 the average $\frac{\rm HCN}{\rm HNC}$ line intensity ratio is 2 for 14 galaxies (excluding limits and their value for Arp 220 (see below)). In our sample, the ratio is somewhat lower, 1.6, when only detections are included (but when limits are included the ratio increases to 2). Joining the H95 galaxies with ours in one sample we still can find no strong trend in the line ratio with increasing FIR luminosity. We note, however, that we have a larger number of galaxies with ratios close to unity (6) compared to H95 (3) despite our smaller sample.

Table 3. Line ratios and FIR luminosities.

Galaxy	type[a]	$\frac{\mathrm{CO}}{\mathrm{CN}}$ 1–0	$\frac{\mathrm{CO}}{\mathrm{HCN}}$ [b]	$\frac{\mathrm{HCN}}{\mathrm{CN}}$	$\frac{\mathrm{HCN}}{\mathrm{HNC}}$	$\frac{\mathrm{HNC}}{\mathrm{CN}}$	CN $\frac{5/2-1/2}{3/2-1/2}$	CN $\frac{2-1}{1-0}$ [c]	log L(FIR)[d]
Arp 220	HII	7.5	8	1	1.6	0.5	...	0.15	12.13
IC 694	HII	$\gtrsim$17	11	$\gtrsim$1.2	1.0[e]	$\gtrsim$1	...	...	11.77
NGC 3690	HII	6	13	0.5	...	...	...	...	...
Mrk 231	Sey 1	8	5	1.6	1	1.6	...	...	12.37
Mrk 273	Sey 2	$\gtrsim$10	2[g]	$\gtrsim$5	$\gtrsim$4	...	...	...	12.04
NGC 34	Sey 2/HII	$\gtrsim$17	4	$\gtrsim$4	$\gtrsim$4	...	...	$\gtrsim$0.35	11.16
NGC 1614	HII	12	14	1	...	...	...	0.35	11.43
NGC 2146	HII	28	16	1.8	...	...	...	...	11.00
NGC 2623	LINER	$\gtrsim$22	12	$\gtrsim$2	1.4	$\gtrsim$1.3	...	...	11.49
NGC 6240	Seyfert 2	18	9	2	2.7	0.7	2.1	0.6	11.69
NGC 3256	HII	29	16	2	3	0.7	2.6	0.14	11.52
NGC 7130	Sey 2/HII	14	13	1.1	1.2	1	2.4	0.25	11.26
NGC 7469	Sey 1/HII	11	8[h]	1.4	1.2	1	...	...	11.41
NGC 1808[f]	HII	13	18	0.7	2	0.4	2.2	0.25	10.48

a) Type of central activity that is suggested to dominate the IR luminosity.
b) The HCN data come from CAB apart from for: IC 694 & NGC 3690 (Arp 299) (Solomon et al. 1992); NGC 1614 (Aalto et al. 1995); NGC 2623, NGC 6240 (Bryant 1996); NGC 3256 (Aalto et al. 1995). The Bryant (1996) ratios are measured with the OVRO interferometer, but since both the CO and HCN emission is compact for both NGC 2623 and NGC 6240 the line ratios are global and can be compared with single dish ratios. For Arp 299 (IC 694 & NGC 3690) the situation is more complicated since the high density tracer emission is emerging from compact structures, while a fraction of the CO emission comes from more extended gas (e.g., Aalto et al. 1997). In Solomon et al. (1992) HCN was measured in a 28″ beam (IRAM).
c) We have not mapped the CN line emission which is of course necessary for an accurate determination of the CN $\frac{2-1}{1-0}$ line ratio. For most galaxies we expect the CN distribution to be effectively a point source in the beam – except for NGC 1808 where we adopt a source size of 18″ (Aalto et al. 1995).
d) The FIR luminosities come from Bryant (1996) (apart from NGC 1808 (Aalto et al. 1994); NGC 34 (CAB); NGC 3256, NGC 7130, NGC 2146 (Aalto et al. 1991))
e) We have assumed that the HNC emission is a point source (see footnote b) and recalculated the line intensity to that of the 28″ IRAM HCN beam.
f) Line ratios are not global, but apply only for the inner 2–3 kpc.
g) We use the temperature line ratio of 2 instead of the integrated line ratio of 1 given in CAB (because the HCN line appear too broad).
h) There is an error in Table 4 of CAB. The correct ratio (8) can be found in Table 3 in CAB.

We observed HNC in Arp 220 to see if we could reproduce the remarkable result in H95 that HNC was brighter than HCN. We observed HNC on two consecutive days, with observations of HCN in between, but could not confirm the bright HNC emission found earlier. Instead we obtain an $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ intensity ratio of 1.4, which is more consistent with results found in other galaxies.

3.1.2. HC_3N

For some galaxies the bandwidth was large enough to include the HC_3N 10–9 line, shifted in velocity by 1000 km s^{-1} from the HNC line. The line is detected in Arp 220 at 40% of the HNC 1–0 intensity. In NGC 1808 the line is tentatively detected at 16% of the HNC 1–0 intensity and in NGC 7130 and NGC 3256 we have upper limits to the line (see footnote to Table 2).

3.2. CN line ratios and intensities

CN 1–0: The line intensities are presented in Table 2 and the ratios in Table 3. The CN 1–0 spectra are displayed in Fig. 3. For most of the galaxies we only observe one of the spingroups in the 1–0 transition. Because of the broad line in Arp 220 the two groups are however blended – even though they are separated by 800 km s^{-1}. Also for NGC 6240 the second spingroup is somewhat blended with the first one.

The $\frac{\mathrm{HCN}}{\mathrm{CN}}$ 1–0 integrated line ratio varies substantially: from 0.5 to greater than four. $I(\mathrm{CN}) \gtrsim I(\mathrm{HCN})$ in three objects (Arp 220, NGC 3690 and NGC 1808), while CN remains undetected in IC 694, Mrk 273, NGC 34 and NGC 2623. We also find three galaxies (Mrk 231, NGC 2623, and IC 694) where $I(\mathrm{CN}) \lesssim I(\mathrm{HNC})$. In four galaxies (Arp 220, NGC 1808, NGC 3256, NGC 6240) $I(\mathrm{HNC}) < I(\mathrm{CN})$ – three are starburst galaxies and NGC 6240 is classified as a Seyfert. In H95, CN was brighter than HNC in all four sample galaxies where CN was measured.

The $\frac{\mathrm{HCN}}{\mathrm{CN}}$ line intensity ratio seems to increase slightly with FIR luminosity. Dividing our galaxies into two luminosity bins we find that the average ratio of 1.5 for the lower luminosity galaxies and 2.3 for the higher luminosity objects. This, somewhat surprising, result is discussed in

Sect. 4.2. We included NGC 3690 in the lower luminosity bin since most of the FIR emission is believed to originate in IC 694.

CN 2–1: The 2–1 spectra are presented in Fig. 4. Both 2–1 spingroups are detected in four of the cases (in NGC 6240 the blending is severe). In NGC 34 and in NGC 1614 we detect only the brighter $J = 5/2$–$3/2$ transition. The CN 2–1 spectrum of Arp 220 shows a much weaker line than the 1–0 spectrum, and emission is only detected in the lower velocity part ($v_c \approx 5200$ km s^{-1}) of the spectrum. Also the CN 1–0 line peaks around 5200 km s^{-1}. The CO emission peaks at $v_c \approx 5400$ km s^{-1}. This implies that most of the CN emission emerges from the western nucleus (see Scoville et al. 1997). The HC_3N line on the other hand appears to peak at $v_c = 5550$ km s^{-1}, and thus most of the emission likely emerges from the eastern nucleus. This tentative velocity difference should be investigated at higher resolution.

3.2.1. The CN $\frac{2-1}{1-0}$ ratio

The CN $\frac{2-1}{1-0}$ line intensity ratio (see footnote to Table 3 on how it was calculated) suggests the CN emission being subthermally excited apart from in NGC 6240 (and NGC 34 with an upper limit to the CN 1–0 emission). In general the ratio is lower than 0.4 indicating gas densities $\lesssim 5 \times 10^4$ cm^{-3} (Fuente et al. 1995) which are about one order of magnitude below the critical density.

3.2.2. The CN spingroup ratio

We can use the 1 mm spingroup ratio to estimate the average optical depth of the two lines. The ratio between the lines is quite large, >2 for all cases where it can be measured. The spingroup ratios are very accurate since they were obtained at the same time (apart from possible baseline errors). In NGC 6240 the line blending is so severe that the ratio is difficult to determine. The LTE ratio should be close to 1.8 (Bachiller et al. 1997) and ratios around 2 thus indicate that the lines are of low optical depth. For most galaxies, the other spingroup of the 1–0 line (around 113.191 GHz ($J = 1/2$–$1/2$)) was outside the observed bandwidth. In the optically thin case, this line is about 1/3 of the $J = 3/2$–$1/2$ at 113.490. For Arp 220, the two lines are blended (see above) and we fitted two Gaussians each centered on one of the spingroups. The fits show that a line intensity ratio between the two lines of 1/3 is possible.

4. Discussion

We initially expected that the relative HNC luminosity would be lower in our sample of warm, luminous galaxies compared to the H95 sample. Instead (see Sect. 3.1.1) the very luminous galaxies even seemed to be somewhat more luminous, on average, in HNC even though this change is not statistically significant. A possibility could be that the telescope beam is picking up more extended, cooler gas in the distant, more luminous, galaxies. However, most of them are known to have very compact molecular cloud distributions and it is unlikely that significant HNC emission emerges from the outskirts of the galaxies. *Our results seem to challenge the notion of HNC as a reliable tracer of cold gas.*

Furthermore, the variation in $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ line ratio is large among the galaxies that otherwise have similar properties. For example, despite having similar $\frac{\mathrm{CO}}{\mathrm{HCN}}$ 1–0 intensity ratios, Mrk 273 and Mrk 231 have quite different $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ and $\frac{\mathrm{HCN}}{\mathrm{CN}}$ line intensity ratios. The $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ ratio of Mrk 231 is close to unity, while HNC is not detected in Mrk 273 resulting in a $\frac{\mathrm{HCN}}{\mathrm{HNC}}$ ratio $\gtrsim 5$. It is unlikely that the dense gas is cold in Mrk 231 but warm in Mrk 273 (both are hot, ultraluminous AGN/Starburst mergers) and therefore the interpretation of HNC needs to be reevaluated.

4.1. Why is HNC often bright in centers of galaxies?

There are a number of possible explanations. Let us examine them one by one and see how they can be tested:

1. *The dense gas is cold*

Is it possible that a significant fraction of the dense gas *is* cold in centers of starburst galaxies? Possibly. Aalto et al. (1994) discuss the presence of cold dense gas in the "mild" starburst galaxy NGC 1808. The high dust temperatures observed towards NGC 1808 could be explained by clouds with hot surfaces and cold interiors. In this scenario, the HNC 1–0 emission would emerge from the cold cloud cores, while HCN 1–0 emission also would come from the outer, warmer parts. Gas at densities $>10^5$ cm^{-3} should become thermalized with the dust. Thus, if the HNC emission is coming from dense, cold (10–20 K) gas there should be submm dust continuum emission associated with it. Therefore, a study of the submm and mm excess in conjunction with the strength of the HNC emission should be quite interesting. However, the most HNC luminous object in our sample, Mrk 213, shows very weak mm thermal dust emission and Braine & Dumke (1998) find a dust temperature of 70 K – the kinetic temperature of the associated dense gas should be at least as high. This is not consistent with the idea that the HNC emission arises from a cold component. Based on ISOPHOT data Klaas et al. (1997) find that the bulk of the dust mass in Arp 220 is at a temperature of about 50 K. Thus, the bright HNC 1–0 emission is unlikely to originate in cold cloud cores.

We conclude that for objects like Mrk 231 and Arp 220, where there is no mm excess emission, and where the overall dust temperature is high, HNC 1–0 does not trace cold dense gas. Instead one or several of the scenarios below must apply. However, for less extreme objects such as NGC 1808 there could be enough mass in cold cores that at least a fraction of the HNC emission could emerge from them.

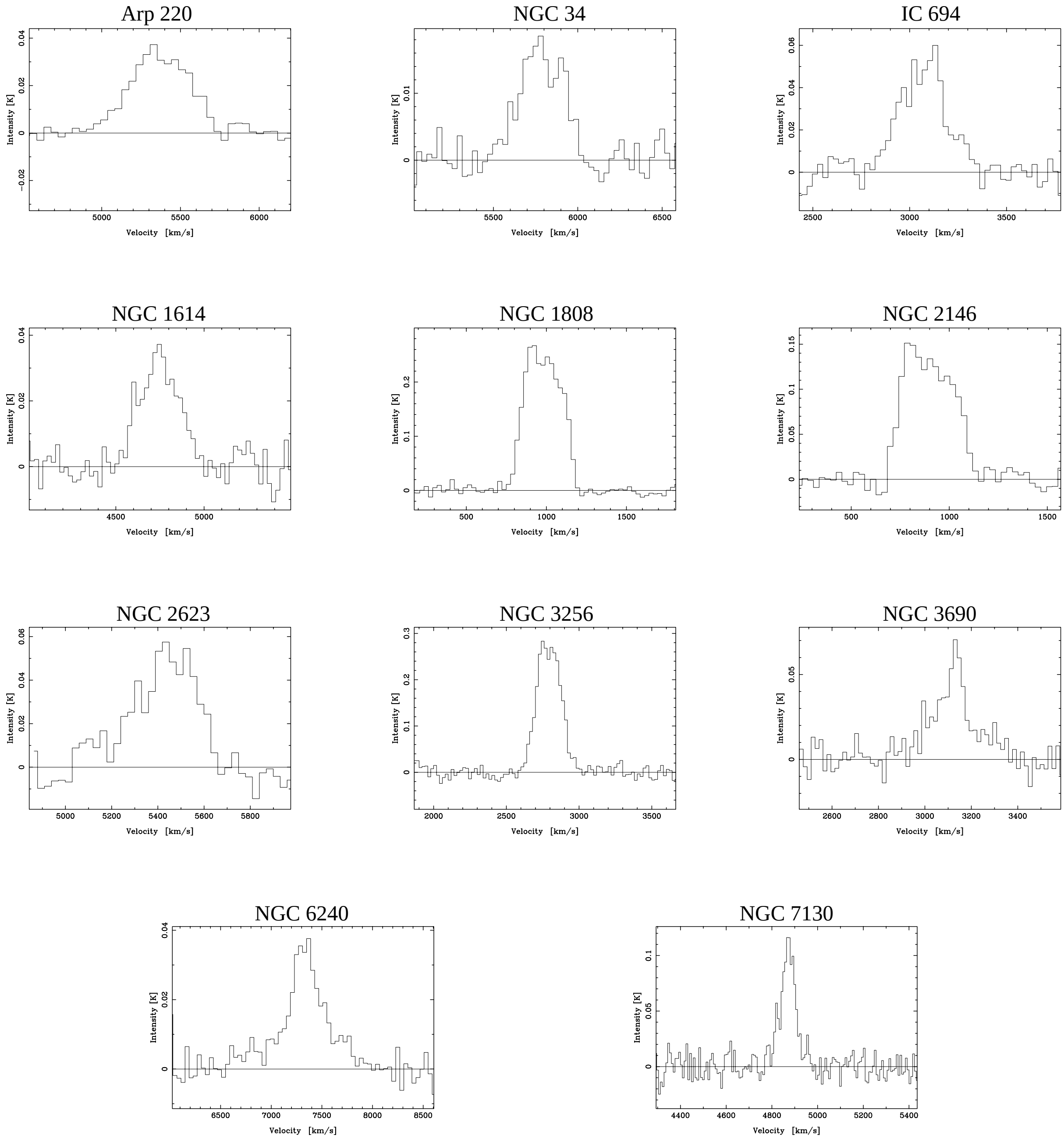

Fig. 1. CO spectra of all galaxies, apart from Mrk 231, Mrk 273 and NGC 7469 which can be found in CAB. The scale is in T_{A}^{*}. The velocity resolution ranges from 10 to 50 $\mathrm{km\,s^{-1}}$. It was selected to be 10% of the FWHM of the line itself.

2. *Chemistry*

Steady state chemistry models by S92 show both a temperature and a density dependence in the $\frac{[\mathrm{HCN}]}{[\mathrm{HNC}]}$ abundance ratio. For example, there is a very significant difference between $n(\mathrm{H_2}) = 10^4$ $\mathrm{cm^{-3}}$ and 10^7 $\mathrm{cm^{-3}}$. For $T_{\mathrm{kin}} = 50$ K, $\frac{[\mathrm{HCN}]}{[\mathrm{HNC}]} = 0.8$ for 10^4 and $\frac{[\mathrm{HCN}]}{[\mathrm{HNC}]} = 67$ for 10^7. If the bulk of the HCN and HNC emission is emerging from gas of densities 10^4–10^5 then the relative HNC abundance there may be substantial, despite the high temperature. The reason for this is that at lower densities reactions with $\mathrm{HCNH^+}$ (HCN and HNC reacts with $\mathrm{H_3^+}$ to form $\mathrm{HCNH^+}$) become more important. The ion abundance is higher and once HCN and HNC become protonised, $\mathrm{HCNH^+}$ will recombine to produce either HCN or HNC with 50% probability. At higher densities, the ion abundance is likely lower and reactions like HNC + O → CO + NH become more important at high temperatures. This scenario is interesting since the electron and ion abundance is likely higher in PDRs. Therefore, in a PDR chemistry, the connection between HNC abundance and kinetic temperature may also be weak since we there expect the $\mathrm{HCNH^+}$ reactions to be important. Since the CN $\frac{2-1}{1-0}$ ratios we measure indicate subthermal excitation it is reasonable to assume

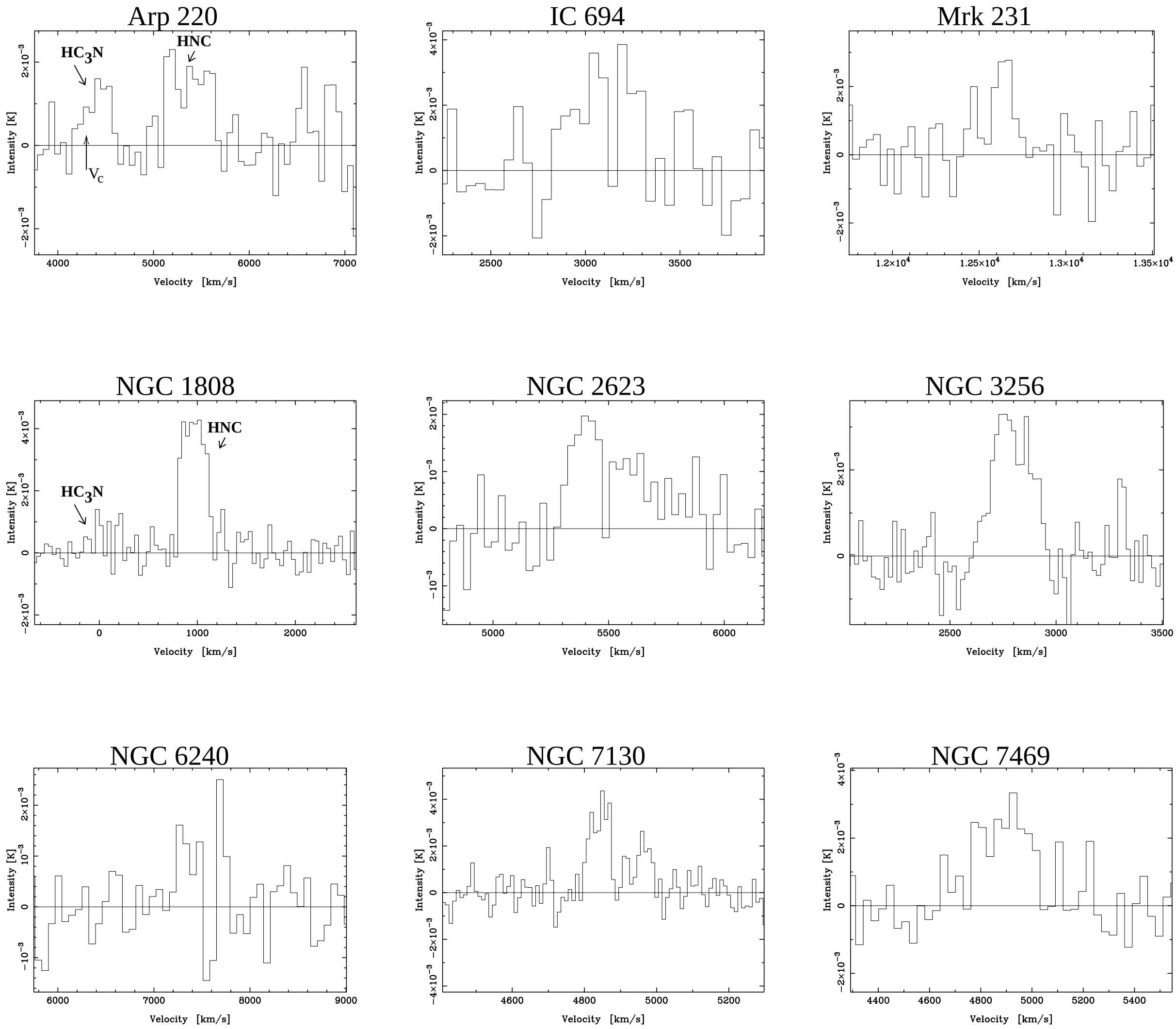

Fig. 2. HNC 1–0 spectra for the galaxies for which we claim a detection. The scale is in T_A^*. The 10–9 HC_3N line is indicated in the spectra for Arp 220 and NGC 1808. The velocity resolution ranges from 10 to 50 $km\,s^{-1}$. It was selected to be 10% of the FWHM of the line itself, but for a few cases the S/N of the spectrum required further smoothing.

that most of the HCN, HNC and CN emission is indeed emerging from gas where the density is below 10^5 cm^{-3}.

3. *Optical depth effects*

In Orion, S92 find peak-to-peak *intensity* ratios between $\frac{HCN}{HNC}$ of 3 to 4 towards the hot core and ridge. However, the abundance ratio is much higher, ≈80. Thus, it is possible that the fairly bright HNC emission in some galaxy centers is caused by optical depth effects. In objects where the HCN emission is subthermally excited (like in Mrk 231) the optical depth of the 1–0 line could be quite high and perhaps explain part of the apparently too-bright HNC.

4. *IR pumping*

Both HCN and HNC may be pumped by an intense mid-IR radiation field boosting the emission from low density regions. There has been no direct evidence IR pumping is dominating the HCN excitation in external galaxies. However, Barvainis et al. (1997) suggest IR pumping as a possible mechanism behind the HCN emission of the Cloverleaf quasar. Ultraluminous galaxies, such as Mrk 231 and Arp 220, have central mid-IR sources with optically thick radiation temperatures well in excess of those necessary to pump the HCN molecule (Soifer et al. 1999). For HNC the coupling to the field is even stronger than for HCN, thus increasing the probability for IR pumping in extreme galaxies, such as Mrk 231. Even if the HNC abundance is lower compared to HCN the HNC emission may have a higher filling factor due to the IR pumping (if it allows emission from gas clouds otherwise at too low density to excite the HNC molecule). A comparative excitation study of HCN and HNC would help cast light on this issue. Of course, the HNC abundance must be high enough so that the pumping can be effective and it must thus happen in regions where the chemistry is dominated by ion-neutral reactions.

4.2. Interpreting the CN emission

4.2.1. CN chemistry

Studies of Galactic molecular clouds have shown that the $\frac{[CN]}{[HCN]}$ abundance ratio is increasing in the outer regions of UV irradiated clouds (e.g., Greaves & Church 1996; Rodriguez-Franco et al. 1998). The abundance of the CN radical becomes enhanced at the inner edge of a PDR (at an A_V of about 2 mag) via the reaction $N + C_2 \rightarrow CN + C$ or via $N + CH \rightarrow CN + H$. At larger depths into the cloud the CN abundance radically declines and the $\frac{[HCN]}{[CN]}$ abundance ratio increases (Jansen et al. 1995). Most of the CN is present in a part of the cloud where the abundance of free electrons is rather large, $X(e) \approx 3 \times 10^{-5}$. CN is also a photodissociation product of HCN. Thus *the CN abundance should be favoured in a molecular cloud ensemble dominated by PDRs*. Furthermore, chemical models (e.g., Krolik & Kallman 1983; Lepp & Dalgarno 1996) show that the CN abundance should also be enhanced when the X-ray ionization rates are high – as might be the case near an AGN.

It is of course difficult to translate a measured $\frac{HCN}{CN}$ 1–0 line intensity ratio to an abundance ratio between the two species. The spingroup line ratios (see Sect. 3.2.1.) show that the CN 2–1 emission is optically thin for most galaxies we have measured. The emission of the CN molecule is distributed in a greater number of transitions than HCN, thus the optical depth per transition is often lower for CN, reducing the intensity per line. The CN luminosity then becomes a measure of the total number of CN molecules (at least in a comparative sense, given a constant excitation situation from galaxy to galaxy). For the CN 1–0 line we have only information for Arp 220 where the relative faintness of the second spingroup suggests that the optical depth of the 1–0 line is also low. So, the measured (total) $\frac{HCN}{CN}$ line intensity ratio will give a reasonable idea of the abundance ratio if also the HCN line is close to being optically thin (and a lower limit to the abundance ratio if it is not) and if the same excitation temperature can be assumed. The critical density of the CN line is lower by a factor of a few, so its T_{ex} is likely somewhat higher.

4.2.2. AGNs or starbursts?

There are only a few galaxies where $I(CN) \gtrsim I(HCN)$ (Arp 220, NGC 3690 and NGC 1808) – all three are starburst galaxies. For these galaxies $N(CN)$ is greater than $N(HCN)$ and the dense gas is to a large degree affected by photodissociation. The most extreme example is NGC 3690 where the CN line is on average more than a factor of two brighter than HCN. In Arp 220 the CN appears to be bright only towards the western of the two nuclei (Sect. 3.2). This is interesting, since the situation is similar for the IC 694/NGC 3690 system: bright CN emission towards one of the galaxy nuclei only. It is interesting to speculate on whether the burst towards NGC 3690 is older than the one in IC 694 because of the development of the PDRs. However, the IC 694 burst is more compact and it is possible that the actual properties of the ISM are intrinsically different.

We were surprised to find that CN was difficult to detect in several of the brightest galaxies like Mrk 273, NGC 2623, NGC 6240, IC 694 and NGC 34. Four of these galaxies are AGNs and it is tempting to speculate that the CN deficiency is related to the nuclear activity. This seems contrary to models (see above) which predict an increase in the CN abundance in an X-ray chemistry. High resolution studies of nearby systems which contain both starburst and AGN activity (like NGC 1068) will reveal whether CN emission is associated with one or both of the activities.

4.2.3. The CN and the [C II] 158 μm line

In ULIRGs such as Arp 220 and Mrk 231 the [C II] 158 μm fine structure line is found to be abnormally faint compared to other, less FIR luminous, starburst galaxies like NGC 3690 (e.g., Luhman et al. 1998). This is interesting, since one would expect the emission from a standard PDR tracer, like the [C II] line, to be bright in a galaxy that is believed to be powered largely by mighty starbursts. Malhotra et al. (1997) report a decreasing trend in $\frac{F_{[CII]}}{F_{FIR}}$ with increasing $\frac{f(60)}{f(100)}$ μm flux ratio.

Several possible explanations for the [C II] faintness are brought forward (e.g., Malhotra et al. 1997; Luhman et al. 1998; van der Werf 2001). The PDRs may be quenched in the high pressure, high density environment in the deep potentials of the ULIRGs and the HII regions exist in forms of small-volume, ultracompact HII regions that are dust-bounded. The [C II] line may become saturated either in low density ($n \propto 10^2$ cm^{-3}) regions of very high UV fields ($G_0 \propto 10^3$) or in dense ($n \propto 10^5$ cm^{-3}) regions of more moderate UV fields ($G_0 = 5$–10). A soft UV field from an aging starburst is another possibility. A higher dust-to-gas ratio would also decrease the expected $\frac{F_{[CII]}}{F_{FIR}}$ ratio.

The molecular ISM of ULIRGs seems to be characterized by subthermally excited CO and very bright emission from HCN (e.g., Downes & Solomon 1998; Aalto et al. 1995; Solomon et al. 1992). Crudely, this can be modelled as dense clouds ($n = 10^4$–10^5 cm^{-3}) embedded in a low density ($n = 100$–500 cm^{-3}) continous medium. This simple scenario may fit well with the two scenarios resulting in saturated [C II] emission.

We have three ULIRGs in our sample: Arp 220, Mrk 231 and Mrk 273 their $\frac{HCN}{CN}$ line intensity ratio changes from 1 to $\gtrsim$6. The deficiency of CN in Mrk 273 is consistent with the lack of [C II] emission and can be an indication that the PDRs are not forming in the dense gas. In Arp 220 the CN emission from the western nucleus is strong and an indicator that a fair fraction of the dense gas is in fact in a PDR state. The UV radiation is strongly affecting the dense molecular clouds here. Clearly we need

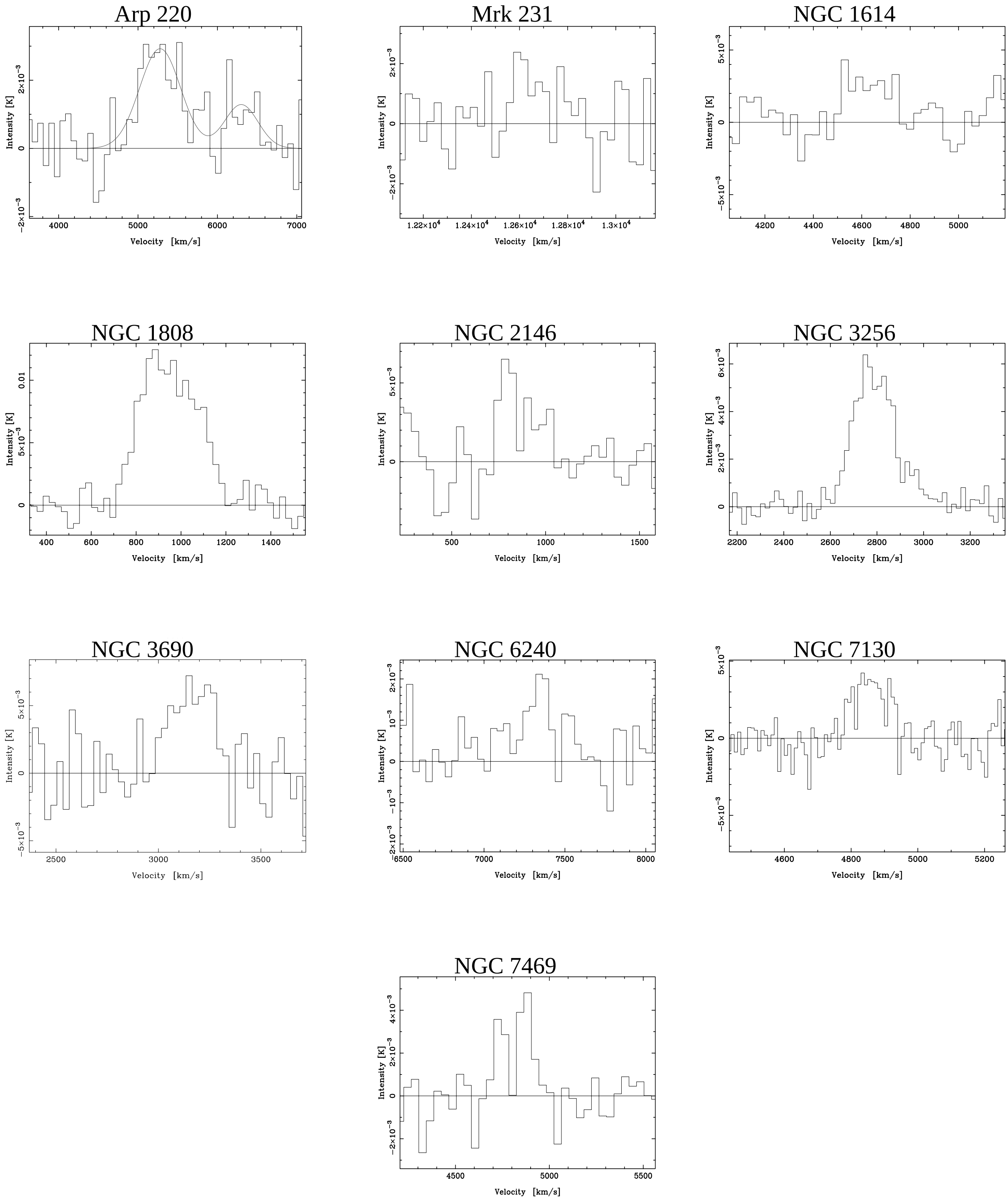

Fig. 3. CN 1–0 spectra for the galaxies with detections. The scale is in T_A^*. The spectrum for Arp 220 shows the Gaussian fit for both spingroups, since the line is broad enough for them to be blended. The velocity resolution ranges from 10 to 50 $km\,s^{-1}$. It was selected to be 10% of the FWHM of the line itself, but for a few cases the S/N of the spectrum required further smoothing.

more information on the properties of the dense gas to find an explanation for the lack of [C II] emission.

4.3. Line ratios and starburst evolution

We speculate whether line ratios of dense gas tracers can be used to explore the evolutionary stage of a starburst. The observed galaxies can be sorted into rough categories based on their line ratios.

4.3.1. Warm dense gas – a young starburst or shocks?

Objects that show bright HCN emission, but little or no HNC or CN, may be dominated by warm dense gas early

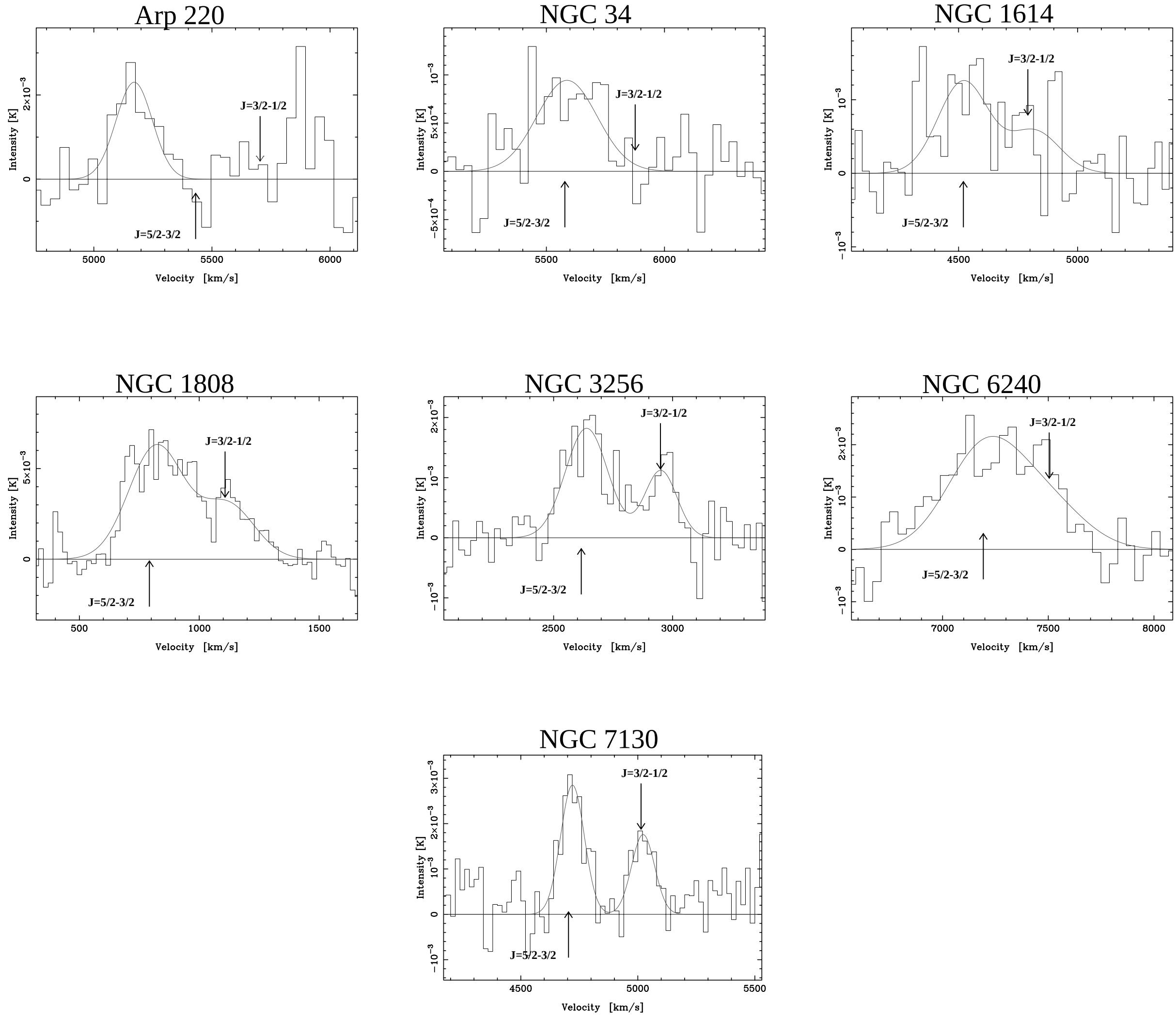

Fig. 4. CN 2–1 spectra for the galaxies with detections. The scale is in $T_{\rm A}^{*}$. The band is centered in between the two spingroups, apart from Arp 220, where the spectrometer was centered on the $J = 5/2$–$3/2$ line. The two spingroups are marked with arrows and are blended for all galaxies, apart from NGC 7130. FOR Arp 220 emission is not detected at the line center (marked by the arrow) instead, there is a tentative detection at $V = 5170$ km s^{-1} (blueshifted from $V_{\rm c}$ by approximately 250 km s^{-1}). The velocity resolution ranges from 10 to 50 km s^{-1}. It was selected to be 10% of the FWHM of the line itself, but for a few cases the S/N of the spectrum required further smoothing.

in their starburst development. The Orion KL region is an example of a Galactic warm ($T \gtrsim 50$ K), dense core where I(HCN) is significantly greater than both I(CN) and I(HNC) (e.g., Ungerechts et al. 1997). Also the emission from the 10–9 transition of HC_3N is brighter than the CN and HNC emission which is a typical signature of warm, dense gas. However, shocked gas may be an important part of the molecular ISM in the center of a starburst galaxy – in particular if there is a bar in the center where clouds on intersecting orbits collide. The interaction between supernova remnants at the surrounding ISM may also lead to the presence of shocked gas. The effect of the shock is to compress and heat the gas, which in some respects will make it look like an ISM dominated by warm dense cores. The major difference is that the shock, partially or fully, destroys the dust grains and thereby releasing molecules, such as SiO, into the ISM. Therefore, SiO emission is often used as a tracer of shocked gas (e.g., Martin-Pintado et al. 1992). If the shocked gas is allowed to cool after the shock (which may happen quickly since it has been compressed) the HNC abundance will increase rapidly (S92). An example of a galaxy that could have a shock dominated ISM is NGC 6240. Very strong IR emission is emerging from shock-excited H_2 (van der Werf 2001) in between the two merger nuclei and both HNC and CN line emission is faint relative to that of HCN. In a high pressure environment the gas may be dense and warm – but perhaps heated by dissipation of turbulence rather than very young embedded stars. This may not occur during the very early stages of star formation, but rather be a form of aftermath.

4.3.2. PDRs

For those galaxies where I(CN) is $\gtrsim I$(HCN) a significant part of the ISM should be in PDRs. In the Galaxy they are often found in interface regions between HII regions and molecular clouds (e.g., Jansen et al. 1995) and near planetary nebulae. CN luminous galaxies are very clearly in the phase where the ISM is being strongly affected by an intense UV field. The filling factor of UV illuminated gas must be high, and the clouds probably not too large since the $\frac{[CN]}{[HCN]}$ abundance ratio drops dramatically with increasing A_V. The mechanical impact of the starburst (superwinds – supernovae) may help in fragmenting the molecular clouds. Emission from complex molecules, such as HC_3N, is faint because of photodestruction. Since the chemistry now, to a large degree, involves ion-neutral reactions (see Sect. 4.1) the HNC abundance becomes less dependent on temperature and I(HNC) may be significant even from a warm PDR. For example, the temperature around a planetary nebula may become very high (≈100 K) but the HNC abundance is substantial enough to result in $\frac{HCN}{HNC}$ line intensity ratios close to unity (e.g., Herpin & Cernicharo 2000).

For Arp 220, it appears that HC_3N is mainly emerging from the eastern nucleus (see Sect 3.2.1) which would support the notion of an evolutionary difference between the two nuclei. Rodriguez-Franco et al. (1998) show that the emission from HC_3N is bright toward hot, dense cores, while the HC_3N/CN abundance ratio is only 10^{-3} in PDRs. Thus the eastern nucleus seems to be in an earlier evolutionary phase where star formation has just begun. In the mid-IR the western nucleus is more prominent than the eastern one (Soifer et al. 1999).

As discussed in Sect. 4.2.1. the absence of PDR tracers, such as CN emission and the 158 μm [C II] fine structure line, does not necessarily mean that the burst is young (or shock dominated). In high-pressure, dusty ULIRGs it is possible that the formation of PDRs is suppressed – or that the PDRs are associated with the diffuse lower density molecular material where the classic PDR lines will not be excited.

4.3.3. An evolved burst

Two galaxies (NGC 2623 and IC 694) show fairly bright HNC emission but with undetected CN emission. Very cold (10 K) and dense gas would result in $I(\mathrm{HCN}) = 0.3{-}0.5 \times I(\mathrm{HNC})$ and $I(\mathrm{CN}) < I(\mathrm{HCN})$. In the Galaxy such conditions dominate clouds like TMC-1 and TMC-2 (e.g., Churchwell et al. 1984). We know, however, from other studies of IC 694 that the dense gas is warm ($T_{\rm kin} \gtrsim$ 80 K) (Aalto et al. 1998) and the compact CO nucleus of NGC 2623 likely harbours an ISM similar to that of IC 694. The starburst may have evolved beyond a strong radiative impact from the stars while the chemisty is still dominated by ion-neutral reactions at moderate gas density and relatively high electron abundance.

5. Summary

We have undertaken a SEST and OSO survey of CN and HNC line emission in a sample of 13 luminous IR galaxies, plus one more "normal" starburst (NGC 1808). This survey is the first in its kind for IR luminous galaxies. The main conclusions we draw from this survey are as follows:

1. We have detected HNC 1–0 in 9 of the galaxies, while CN 1–0 is detected in 10 galaxies. The CN 2–1 lines ($J = 5/2$–$3/2$, $F = 7/2$–$5/2$; $J = 3/2$–$1/2$ $F = 5/2$–$3/2$) (which could only be measured at SEST) are detected in 7 galaxies – in one (NGC 34) the CN 1–0 line was not detected, while the 2–1 line was.
2. The line intensitites vary significantly from galaxy to galaxy and the line ratios relative to the "standard" high density tracer, HCN, are far from constant. The $\frac{HCN}{HNC}$ ratios vary from 1 to $\gtrsim$6 and the $\frac{HCN}{CN}$ ratios range from 0.5 to $\gtrsim$6. From this we can learn that the actual properties of the dense gas vary significantly from galaxy to galaxy, even if their HCN luminosities are similar.
3. We report the detection of HC_3N 10–9 emission in Arp 220 at 40% of the HNC 1–0 intensity. In NGC 1808 the line is tentatively detected.
4. We find that the IR luminous galaxies are at least as HNC luminous as more nearby (IR-fainter) galaxies. We conclude that the HNC emission is not a reliable tracer of cold (10 K) gas in the center of luminous IR galaxies, the way it may be in clouds in the disk of the Milky Way. Instead, we list several alternative (testable) explanations. Provided that the situation in the centers of starburst galaxies can be approximated with a steady state chemistry, the observed $\frac{HCN}{HNC}$ line ratios can be explained by the emission originating in gas of densities $n \lesssim 10^5$ cm^{-3} where the chemistry is dominated by ion-neutral, instead of neutral-neutral, reactions. The temperature dependence of the HNC production in the ion-neutral reactions is strongly suppressed.
5. We were surprised to find that the CN emission of the more luminous galaxies is often faint. This can be consistent with the relative faintness of other PDR tracers such as the 158 μm [C II] line. Both these phenomena can be understood in terms of a two-component molecular ISM consisting of low density molecular gas surrounding dense clouds. However, the relative brightness of CN in Arp 220 may be difficult to reconcile with its relative [C II] faintness.
6. Within Arp 299 (the merging pair IC 694 and NGC 3690) there is a line ratio difference between the two nuclei. NGC 3690 has a CN luminosity twice that of HCN and its ISM is thus strongly affected by UV radiation while CN is not detected towards IC 694. This reflects an evolutionary gradient in the burst – or that the star formation activity takes place in very different environments in the two galaxies. For Arp 220 there may also be an evolutionary gradient between the two

nuclei because of differences in emission velocities for CN and HC_3N.

7. The measured line ratios can in general be used to identify stages in the starburst evolution, but we conclude that the dichotomy between scenarios is a complication. For example, faint HNC emission is expected both in a shock dominated ISM as well as for a cloud ensemble dominated by dense warm gas in the very early stages of a starburst.

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References

Aalto, S., Black, J. H., Booth, R. S., & Johansson, L. E. B. 1991, A&A, 247, 291
Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1994, A&A, 286, 365
Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1995, A&A, 300, 369
Aalto, S., Radford, S. J. E., Scoville, N. Z., & Sargent, A. I. 1997, ApJ, 475, L107
Aalto, S., Radford, S. J. E., Scoville, N. Z., & Sargent, A. I. 1998, IAU Symp. 186, Galaxy Interactions at Low and High Redshift, ed. D. Sanders
Bachiller, R., Fuente, A., Bujarrabal, V., et al. 1997, A&A, 319, 235
Barvainis, R., Maloney, P., Antonucci, R., & Alloin, D. 1997, ApJ, 484, 695
Braine, J., & Dumke, M. 1998, A&A, 333, 38
Bryant, P. M. 1996, Ph.D. Thesis, Caltech
Bryant, P. M., & Scoville, N. Z. 1999, AJ, 117, 2632
Churchwell, E., Nash, A. G., & Walmsley, C. M. 1984, ApJ, 287, 681
Curran, S. J., Aalto, S., & Booth, R. S. 2000, A&AS, 141, 193 (CAB)
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Fuente, A., Martin-Pintado, J., & Gaume, R. 1995, ApJ, 442, L33
Greaves, J. S., & Church, S. E. 1996, MNRAS, 283, 1179
Helfer, T. T., & Blitz, L. 1993, ApJ, 419, 86
Herpin, F., & Cernicharo, J. 2000, ApJ, 530, L129
Hüttemeister, S., Henkel, C., Mauersberger, R., et al. 1995, A&A, 295, 571
Jansen, D. J., van Dishoeck, E. F., Black, J. H., Spaans, M., & Sosin, C. 1995, A&A, 302, 223
Klaas, U., Haas, M., Heinrichsen, I., & Schulz, B. 1997, A&A, 325, L21
Krolik, J. H., & Kallman, T. R. 1983, ApJ, 267, 610
Lepp, S., & Dalgarno, A. 1996, A&A, 306, L21
Luhman, M. L., Satyapal, S., Fischer, J., et al. 1998, ApJ, 504, L11
Malhotra, S., Helou, G., Stacey, G., et al. 1997, ApJL, 491, 27
Martin-Pintado, J., Bachiller, R., & Fuente, A. 1992, A&A, 254, 315
Polatidis, A., & Aalto, S. 2000, in Proc. of the 5th EVN Symp., ed. J. Conway, A. Polatidis, R. Booth., & Y. Pihlström, Onsala Space Observatory, Chalmers Technical University, Gothenburg, Sweden (2000), 127
Rodriguez-Franco, A., Martin-Pintado, J., & Fuente, A. 1998, A&A, 329, 1097
Schilke, P., Walmsley, C. M., Pineau de Forêts, G., et al. 1992, A&A, 256, 595 (S92)
Scoville, N. Z., Yun, M. S, & Bryant, P. M. 1997, ApJ, 484, 702
Soifer, B. T., Neugebauer, G., Matthews, K., et al. 1999, ApJ, 513, 207
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 387, L55
Ungerechts, H., Bergin, E. A., Goldsmith, P. F., et al. 1997, ApJ, 482, 245
van der Werf, P. P. 2001, in Starburst galaxies – near and far, proceedings of the Ringberg workshop, ed. D. Lutz, & L. J. Tacconi, in press
Wall, W. F., Jaffe, D. T, Bash, F. N., et al. 1993, ApJ, 414, 98
Wild, W., Harris, A. I., Eckart, A., et al. 1992, A&A, 265, 447